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IMPACT CRATERING AT GEOLOGIC STAGE BOUNDARIES

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Abstract. The largest known Cenozoic impact craters with the most accurately measured ages are found to correlate very closely with geologic stage boundaries. The level of confidence in this result is 98-99% even under the most pessimistic assumptions concerning dating errors. One or more large impacts may have led, in at least some cases, to the extinctions and first appearances of biotic species that mark many of the geologic stage boundaries.

Introduction

Ever since Alvarez et al. (1980) discovered an anomalous iridium layer at the Cretaceous/Tertiary boundary, the startling hypothesis of a devastating impact by a large extraterrestrial body has figured in discussions of the mass extinction of biotic species at this and other major period boundaries. In light of the fact that most of the geologic stage boundaries are now usually tied to observed extinctions and first appearances of marine species, it has been occasionally suggested that large or frequent impacts caused, either directly or indirectly, the turnover of species at these lesser boundaries as well (Urey, 1973; Rampino and Stothers, 1987; Raup, 1992). Owing to an insufficiency of data, however, this hypothesis has been forced to remain purely speculative. With very recent improvements in the measured ages of impact craters and in the geologic time scale, and with a suitable methodology, it is now possible to test the hypothesis critically for the first time.

Although a huge structure of possible impact origin, Chicxulub in Mexico, has already been provisionally correlated with the Cretaceous/Tertiary boundary (Hildebrand et al., 1991), a statistic of one is not conclusive. If it were to be found that known, well-dated craters of smaller size also correlate with stage boundaries, the clear implication would be that impacts occur in brief showers and hence it would be unnecessary to locate a very large crater in order to establish a cratering episode; a lesser crater would do. Previously, attempts were made to do this by looking for similar patterns of periodicity in cratering and extinction rates. A proposed ~30 Myr cratering periodicity, however, has apparently now collapsed as the result of recent improvement in the crater ages (Grieve, 1991). Debate still continues about whether the extinction data show a comparable periodicity (Sepkoski, 1989). A more refined approach to the problem of a possible correlation is clearly needed.

Data and Methods

Grieve (1991) has published a revised list of large, well-dated impact craters that were formed during Cenozoic time. Diameters of all these craters exceed 5 km. To this list might now be added the 180 km diameter Chicxulub structure with an $^{40}Ar/^{39}Ar$ age of 65.0 ± 0.1 Myr (Swisher et al., 1992; Sharpton et al., 1992), but, being an uncertain impact crater, it will be omitted here.

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Seven of these objects have isotopic ages with such small 1σ analytical errors (less than or equal to ±1 Myr) that they can be realistically compared with the very accurately measured ages of Cenozoic stage boundaries (which have an average spacing of 3.8 Myr). These seven craters and their ages are listed in Table 1. The four youngest ages are based chiefly on the K/Ar method (Shoemaker and Wolfe, 1986; Grieve, 1991), while the three oldest are $^{40}Ar/^{39}Ar$ based (Jessberger, 1988; Bottomley and York, 1988; Kunk et al., 1989). The $^{40}Ar/^{39}Ar$ age of 15.1 Myr for the Ries crater (Staudacher et al., 1982) agrees well with its K/Ar age. The five ages younger than ~30 Myr can be checked by the somewhat more precise (though not necessarily more accurate) fission track method, which yields 1.07 ± 0.05, 1.04 ± 0.11, 4.5 ± 0.1, 14.7 ± 0.4, and 21.5 ± 1.2 Myr, respectively (Shoemaker and Wolfe, 1986; Grieve, 1991). For the Haughton crater, the original fission track age was 22.4 ± 1.4 Myr (Omar et al., 1987), but Grieve's (1991) slightly adjusted value is adopted here. There is no reason to doubt the relatively high accuracy of the $^{40}Ar/^{39}Ar$ ages measured for the two craters older than ~30 Myr. Two of the seven well-dated craters, Bosumtwi and Ries, correlate both temporally and spatially with known tektite strewnfields: the Ivory Coast (1.0 ± 0.1 Myr) (Glass et al., 1991) and the Czechoslovakian (14.7 ± 0.6 Myr) (Glass, 1982). These tektite ages independently confirm the small published analytical errors of the corresponding crater ages. It seems safe to conclude that the ages of the seven selected craters are reliable enough to be used here. Stratigraphic ages, available for some of the craters, cannot be used in the analysis, because they are obviously not independent of the stage boundary ages, whose unbiased correlation with impact cratering is being sought.

A comparison between the seven best-measured crater ages and the stage boundary ages nearest to them is presented in Table 1. The list of stage boundary ages displays the range of three more-or-less independent Cenozoic times scales: Harland et al. (1990), Haq and Van Eysinga (1987) (supplemented by Haq et al., 1987), and Berggren et al. (1985). The DNAG time scale (Palmer, 1983) is essentially the same as that of Berggren et al. (1985).

Agreement between the crater ages and boundary ages is very close. To test its statistical significance, the rms difference (or, alternatively, the median absolute difference) between nearest neighbors in the two parallel time series is calculated and adopted as a correlation measure, in analogy with least-squares fitting and chi-square testing. Estimated errors in the observed times, as well as a uniform shift of one series with respect to the other to accommodate an unknown phase mismatch, are incorporated into the analysis through the multiple generation of slightly perturbed (pseudo-randomized) time series. The significance level of the average correlation measure at the average position of the best phase match is computed by performing Monte Carlo simulations. Many random time series, each containing the same number of times as in the observed series that is chosen to be the target series (here, the sequence of crater ages), are produced, internally time-ordered, and cross-correlated with the other observed series which is being treated as the template series (here, the sequence of stage boundary ages). The random times are uniformly distributed random

TABLE 1. Well-Dated Large Cenozoic Impact Craters and the Nearest Geologic Stage Boundaries

Impact crater*	Age (Myr)	Stage boundary	Boundary age (Myr)
Zhamanshin	0.9 ± 0.1	Piacenzian/Calabrian	1.60 – 1.67
Bosumtwi	1.3 ± 0.2	Piacenzian/Calabrian	1.60 – 1.67
Elgygytgyn	3.5 ± 0.5	Zanclian/Piacenzian	3.4 – 3.5
Ries	14.8 ± 0.7	Langhian/Serravallian	14.2 – 15.2
Haughton	23.4 ± 1.0	Chattian/Aquitanian	23.3 – 24.0
Montagnais	50.5 ± 0.8	Ypresian/Lutetian	50.0 – 52.0
Manson	65.7 ± 1.0	Maastrichtian/Danian	65.0 – 66.4

*Omitting the Chicxulub structure with an age of 65.0 ± 0.1 Myr.

variables lying within the same preassigned time interval as the observed times of the target series. The percentage of random correlations that are better than the observed correlation within a symmetrical range of possible phase match positions extending up to the observed best position formally represents the estimated significance level.

Results

Three different correlation analyses (corresponding to the three different Cenozoic time scales) have been performed on the seven crater ages, utilizing as a template series the list of 19 stage boundaries between the Campanian/Maastrichtian boundary (74 Myr) and the Pleistocene/Holocene boundary (0.01 Myr). All of the analyses pseudo-randomize the crater ages within their estimated gaussian error distributions.

The results in Table 2 indicate an extremely tight correlation. The most pessimistic assumptions about possible errors in the crater ages confirm a highly significant correlation, at a level of 1% to 2%. If an average of the three different Cenozoic time scales is adopted and a 1σ analytical error of ±1 Myr (estimated value) is assigned to all of the stage boundaries older than the Piacenzian/Calabrian (Harland et al., 1990), the significance level shifts to 2.6%. If fission track ages are adopted for the five youngest craters, the significance levels change insubstantially.

Relaxation of the constraints on crater diameter, age, and analytical age error has also been examined. If the cutoff for the crater diameters is reduced to zero, many recently formed craters of very small size must be added, biasing the statistics toward the present time. All of these well-dated minor craters, except Steinheim, possess ages of less than 4 Myr (Grieve, 1991) and represent a quickly eroded record of the frequent, small background impactors. Assigning a more reasonable cutoff diameter of 2 km adds only New Quebec (1.4 ± 0.1 Myr) (Grieve et al., 1991), Roter Kamm (3.7 ± 0.3 Myr) (Hartung et al., 1991), and Steinheim (14.8 ± 0.7 Myr) (Reiff, 1977) to Table 1. For completeness, the possible Chicxulub crater will also be added. These 11 craters are found to correlate with geologic stage boundaries at the 0.2% level. If analytical errors in the stage boundary ages are also used, the significance level is still very low, 1.0%.

Dividing the craters by age, on the other hand, reduces the available statistics. The five craters younger than the age of the Serravallian/Tortonian boundary (10.4 Myr) show the same correlation at a level of 4%, while the six older ones do so at the 2% level.

Could pre-Cenozoic craters be used? No matter how accurately dated, these craters are not useful for the present purpose, because the uncertainties of the published stage boundary ages become comparable to the stage half-lengths (or even more) before the middle Cretaceous (Harland et al., 1990).

Although it is possible to raise the 1σ analytical error limit for Cenozoic craters to ±2 Myr, nothing practical is gained. Four additional large craters appear to be usable, but actually are not: Popigai and Wanapitei both have isotopic and fission track ages

TABLE 2. Results of Cross-Correlation Analysis of Impact Crater Ages and Stage Boundary Ages

Stage boundary ages	Impact crater ages*	Average residual (Myr)	Significance level (%)
Harland et al.	Ar	0.5	1.4
	FT mainly	0.6	1.4
Haq and Van Eysinga	Ar	0.6	1.4
	FT mainly	0.6	1.4
Berggren et al.	Ar	0.6	2.1
	FT mainly	0.5	1.2

*Ar = isotopic age. FT = fission track age.

that formally differ from each other by approximately 5 Myr, while Kamensk and Marquez Dome have been only stratigraphically dated (Shoemaker and Wolfe, 1986; Grieve, 1991).

Discussion

When the number of sizable, well-dated craters in the sample is increased from 5, to 6, to 7, to 11, the significance level of the correlation between impact cratering and termination of geologic stages drops from 4%, to 2%, to 1.4%, to 0.2%, for any of the modern geologic time scales used. Just the opposite trend would be expected if the correlation were only a statistical accident due to sampling bias.

As far as phase is concerned, impacts formally lag or lead stage boundaries by small amounts whose mean is smaller than or equal to the rms residual of the overall fit and so is not statistically distinguishable from zero. The 2σ two-tail spread of the residuals is ~2 Myr. If this is mostly physical, it agrees with rough independent estimates (made in various ways) for the average duration of a shower of impactors and for the typical length of an observed extinction episode (Hut et al., 1987).

The impactors that produced the 10-45 km diameter craters listed in Table 1 are of course not necessarily the specific ones that could have led, directly or indirectly, to the extinctions and first appearances of biota defining major biostratigraphic zones and hence most stages. Certainly, the size range and frequency of impactors needed for that purpose are not yet known; both may be bigger for large extinction events. Location of impact and vulnerability of the biota must also play a role. However, the accumulation of small environmental disruptions, either regional or global, by a succession of minor impacts over a period of ~2 Myr could possibly produce the kind of limited faunal turnover seen near lesser stage boundaries, at least in the case of some stage boundaries.

Alternatively, one large impact might lead to a flood basalt eruption, which could then cause the necessary environmental deterioration. There is now some statistical and physical evidence for impact-induced flood basalt vocanism (Alt et al., 1988; Stothers and Rampino, 1990), as well as a remarkably good temporal correlation between continental flood basalt eruptions and the stage boundaries where mass extinctions occurred during Cenozoic and Mesozoic time (Rampino and Stothers, 1988; Stothers, 1993a). Since the estimated number of all flood basalts on the continents and in the ocean basins during this time roughly equals the total number of geologic stages (Stothers, 1993b), impact-induced flood basalts could be the cause of at least some of the biotic changes seen near stage boundaries.

These conclusions obviously differ from the more traditional interpretations of the record based on the assumption of purely endogenic changes of volcanism, climate, sea level, and ocean chemistry (e.g., Hallam, 1987; Crowley and North, 1988). They also diverge in significant ways from Raup's (1992) simple impact-kill hypothesis with its approximate one-to-one relationship between crater diameter and magnitude of extinction event. Like the other interpretations, the present interpretation can be tested further by accumulating more geologic, geochemical, paleontological, and cratering data resolved at the substage level.

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References

Alt, D., J.M. Sears, and D.W. Hyndman, Terrestrial maria: the origins of large basalt plateaus, hotspot tracks and spreading ridges, *J. Geol.*, *96*, 647-662, 1988.

Alvarez, L.W., W. Alvarez, F. Asaro, and H.V. Michel, Extraterrestrial cause for the Cretaceous-Tertiary extinction, *Science*, *208*, 1095-1108, 1980.

Berggren, W.A., D.V. Kent, J.J. Flynn, and J.A. Van Couvering, Cenozoic geochronology, *Geol. Soc. Amer. Bull.*, *96*, 1407-1418, 1985.

Bottomley, R., and D. York, Age measurement of the submarine Montagnais impact crater, *Geophys. Res. Lett.*, *15*, 1409-1412, 1988.

Crowley, T.J., and G.R. North, Abrupt climate change and extinction events in Earth history, *Science*, *240*, 996-1002, 1988.

Glass, B.P., Possible correlations between tektite events and climatic changes? *Geol. Soc. Amer. Spec. Pap.*, *190*, 251-256, 1982.

Glass, B.P., D.V. Kent, D.A. Schneider, and L. Tauxe, Ivory Coast microtektite strewn field: description and relation to the Jaramillo geomagnetic event, *Earth Planet. Sci. Lett.*, *107*, 182-196, 1991.

Grieve, R.A.F., Terrestrial impact: the record in the rocks, *Meteoritics*, *26*, 175-194, 1991.

Grieve, R.A.F., R.B. Bottomley, M.A. Bouchard, P.B. Robertson, C.J. Orth, and M. Attrep, Jr., Impact melt rocks from New Quebec Crater, Quebec, Canada, *Meteoritics*, *26*, 31-39, 1991.

Hallam, A., End-Cretaceous mass extinction event: argument for terrestrial causation, *Science*, *238*, 1237-1242, 1987.

Haq, B.U., J. Hardenbol, and P.R. Vail, Chronology of fluctuating sea levels since the Triassic, *Science*, *235*, 1156-1167, 1987.

Haq, B.U., and F.W.B. Van Eysinga, *Geological Time Table*, Elsevier, Amsterdam, 1987.

Harland, W.B., R.L. Armstrong, A.V. Cox, L.E. Craig, A.G. Smith, and D.G. Smith, *A Geologic Time Scale 1989*, Cambridge University Press, Cambridge, 1990.

Hartung, J.B., M.R. Kunk, W.U. Reimold, R.M. Miller, and R.A.F. Grieve, Roter Kamm crater age: 3.5 to 4.0 Ma, *Meteoritics*, *26*, 342-343, 1991.

Hildebrand, A.R., G.T. Penfield, D.A. Kring, M. Pilkington, A. Camargo, S.B. Jacobsen, and W.V. Boynton, Chicxulub Crater: a possible Cretaeous/Tertiary boundary impact crater on the Yucatán Peninsula, Mexico, *Geology*, *19*, 867-871, 1991.

Hut, P., W. Alvarez, W.P. Elder, T. Hanson, E.G. Kauffman, G. Keller, E.M. Shoemaker, and P.R. Weissman, Comet showers as a cause of mass extinctions, *Nature*, *329*, 118-126, 1987.

Jessberger, E.K., ^{40}Ar-^{39}Ar dating of the Haughton impact structure, *Meteoritics*, *23*, 233-234, 1988.

Kunk, M.J., G.A. Izett, R.A. Haugerud, and J.F. Sutter, ^{40}Ar-^{39}Ar dating of the Manson impact structure: a Cretaceous-Tertiary boundary crater candidate, *Science*, *244*, 1565-1568, 1989.

Omar, G., K.R. Johnson, L.J. Hickey, P.B. Robertson, M.R. Dawson, and C.W. Barnosky, Fission-track dating of Haughton astrobleme and included biota, Devon Island, Canada, *Science*, *237*, 1603-1605, 1987.

Palmer, A.R., The Decade of North American Geology 1983 geologic time scale, *Geology*, *11*, 503-504, 1983.

Rampino, M.R., and R.B. Stothers, Episodic nature of the Cenozoic marine record, *Paleoceanography*, *2*, 255-258, 1987.

Rampino, M.R., and R.B. Stothers, Flood basalt volcanism during the past 250 million years, *Science*, *241*, 663-668, 1988.

Raup, D.M., Large-body impact and extinction in the Phanerozoic, *Paleobiology*, *18*, 80-88, 1992.

Reiff, W., The Steinheim Basin: an impact structure, in *Impact and Explosion Cratering*, edited by D.J. Roddy, R.O. Pepin, and R.B. Merrill, pp. 309-320, Pergamon, New York, 1977.

Sepkoski, J.J., Jr., Periodicity in extinction and the problem of catastrophism in the history of life, *J. Geol. Soc. London*, *146*, 7-19, 1989.

Sharpton, V.L., G.B. Dalrymple, L.E. Marín, G. Ryder, B.C. Schuraytz, and J. Urrutia-Fucugauchi, New links between the Chicxulub impact structure and the Cretaceous/Tertiary boundary, *Nature*, *359*, 819-821, 1992.

Shoemaker, E.M., and R.F. Wolfe, Mass extinctions, crater ages, and comet showers, in *The Galaxy and the Solar System*, edited by R. Smoluchowski, J.N. Bahcall, and M.S. Matthews, pp. 338-386, University of Arizona Press, Tucson, 1986.

Staudacher, T., E.K. Jessberger, B. Dominik, T. Kirsten, and O.A. Schaeffer, ^{40}Ar-^{39}Ar ages of rocks and glasses from the Nördlinger Ries Crater and the temperature history of impact breccias, *J. Geophys.*, *51*, 1-11, 1982.

Stothers, R.B., Flood basalts and extinction events, *Geophys. Res. Lett.*, in press, 1993a.

Stothers, R.B., Hotspots and sunspots: surface tracers of deep mantle convection in the Earth and Sun, *Earth Planet. Sci. Lett*, in press, 1993b.

Stothers, R.B., and M.R. Rampino, Periodicity in flood basalts, mass extinctions, and impacts: a statistical view and a model, *Geol. Soc. Amer. Spec. Pap.*, *247*, 9-18, 1990.

Swisher, C.C., III, J.M. Grajales-Nishimura, A. Montanari, S.V. Margolis, P. Claeys, W. Alvarez, P. Renne, E. Cedillo-Pardo, F.J.M.R. Maurrasse, G.H. Curtis, J. Smit, and M.O. McWilliams, Coeval $^{40}Ar/^{39}Ar$ ages of 65.0 million years ago from Chicxulub Crater melt rock and Cretaceous-Tertiary boundary tektites, *Science*, *257*, 954-958, 1992.

Urey, H.C., Cometary collisions and geological periods, *Nature*, *242*, 32-33, 1973.

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